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Abstract
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Disciplines
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Implementing Advanced Wireless Sensing System for Airfield Pavement Condition Monitoring

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ABSTRACT

Real-time monitoring of pavement conditions is beneficial not only to more accurate predictions of airport pavement performance but also to more efficient pavement management activities. Although wireless-based sensing system have shown some advantages compared to wired sensing system, there are just few studies that describe instrumenting wireless sensors in the field for pavement condition monitoring. To bridge this gap, this paper presents case studies describing use of advanced wireless sensing system for airport pavement conditions monitoring at three test sites: the Des Moines International Airport (DSM), the Ohio State University (OSU) Airport, and the Texas A&M University (TAMU) Airport. The wireless sensors communicate through a gateway to collect sensor data and then upload it to the cloud. The wireless sensor instrumentation strategy and design plans, based on the field instrumentation experience, are summarized. The key requirements and potential restrictions for implementing wireless sensing systems in airfield pavement are also discussed.

INTRODUCTION

Airfield pavement deterioration caused by mechanical loads from aircraft and environmental loads from cyclic temperature and moisture variations can be major concerns with respect to airport safety. Such distress-developing processes can impair airfield pavement functional and structural behaviors and may hinder airport operation management. Unlike a highway pavement system, an airfield pavement typically has less loading events per day, but with much higher aircraft tire pressure. As a result of continuous exposure to sun, rain, snow, and other weather-related effects, airfield pavements particularly show excessive environmental-load-related deterioration, including weathering, raveling, and cracking (FAA, 2011), so it is important to monitor the impact of diurnal and seasonal weather changes on airfield pavements.

Real-time monitoring of pavement conditions is essential for airfield pavement management to support not only more accurate predictions of airport pavement life and performance but also efficient pavement management activities for preventing pavement failure prior to its actual occurrence. For example, tracking pavement temperature and moisture profiles can effectively increase awareness of excessive temperature and moisture build-up within slabs, which may cause blowup at the joints (not common in airport pavement) or other thermal stresses related cracks (Yang, et al., 2014).

Similar to conventional highway pavement, airfield pavement also involves full-scale pavement test sections instrumented with large numbers of sensors such as strain gauges, pressure cells, temperature sensors, etc. Table 1 summarizes previous projects involving airfield pavement instrumentation in the U.S., which the main type of implementation is to use wired sensors coupled with a mobile data acquisition system. Traditional use of wired sensors is generally time-consuming and costly and also involves a relatively complicated design process due to cable length and limited channels. When a large number of wired sensors are installed, the total cost can be incredibly high (Cho, et al., 2008; Lynch, et al, 2003). In addition to potentially high installation cost, wired sensor systems are also susceptible to wire damage in pavement due to corrosion, which is almost impossible to repair in the field.

Table 1. Previous Instrumented Pavement Sections in U.S. Airport.

Project Location	Monitoring System	Year	Reference
Runway at Denver International Airport	Strain gages, thermocouples, and time domain reflectometers	1996	Lee et al., 1997
FAA National Airport Pavement Test Facility	Strain gages, temperature sensors, and moisture sensors	1997	Hayhoe 2004
Taxiway at Hartsfield-Jackson International Airport	Deflection transducers, strain gages, and temperature sensors	2006	Brill et al., 2007
Runway at Newark Liberty International Airport	Strain gages and temperature sensors	2012	Cook 2014
Taxiway in John F Kennedy International Airport	Strain gages, pressure gages, and temperature sensors	2010	Garg et al., 2013
LaGuardia Intl. Airport	Strain gages	N/A	FAA 2017

As promising sensing paradigms, wireless sensors based systems have been extensively investigated during the 21st century because of their capability for providing advanced pavement condition monitoring to overcome limitations of conventional wired sensor systems. Wireless sensor systems can offer improvements in installation processes, data aggregation, signal analysis, sensor clustering, event localization, time synchronization, measurement progress, discrete monitoring, event-based monitoring, and cost saving (Yang 2014). They also reduce the threat of wire damage in pavement and enhance flexibility for more economical and efficient pavement condition monitoring. However, although wireless sensing systems are not new to pavement engineers, there are only a few studies that describe instrumenting wireless sensors in the field for pavement-condition monitoring purposes and related to issues that include on-site power supply, battery life, wireless communication, and data transfer. To bridge this gap, this paper presents case studies describing use of advanced wireless sensing systems for monitoring airport pavement conditions.

WIRELESS SENSOR SYSTEM FOR PAVEMENT CONDITION MONITORING

Wireless sensor systems have begun to draw attention for pavement condition monitoring since the end of the 20th century. It should be noted that a wireless sensor system utilized for pavement applications might not be completely “wireless”. When a wireless sensor system is embedded in a pavement structure, it is not possible to subsequently and non-destructively take out the power unit. Its operation must totally rely on battery lifetime, which can be greatly diminished under harsh environmental conditions (Yang, et al., 2015). Furthermore, it will have less communication range as well if it was buried underground. To resolve this issue, an alternative solution would be to have the sensing components buried in the pavement system but with a wireless transmission unit and batteries stored outside. The sensing components in such a system would be connected to the wireless transmission unit by durable cables.

Monnit wireless system. The Monnit wireless sensor system consists of a set of temperature probes for data measurements and a gateway for data uploading (see Figure 1). In this system, the probe can detect temperature and transmit data through an antenna on the sensor head (wireless transmission unit). The gateway (wireless receiver) can capture the signals with a maximum communication distance about 90 m and subsequently upload them to the cloud through the cellular or Ethernet network. Additionally, the gateway has an embedded memory module so data can be stored in the gateway when the network is temporally disabled. After data uploading, a website-based software would organize all the data and permit access only by authorized users for viewing the readings, plots, signal strength, and battery status.

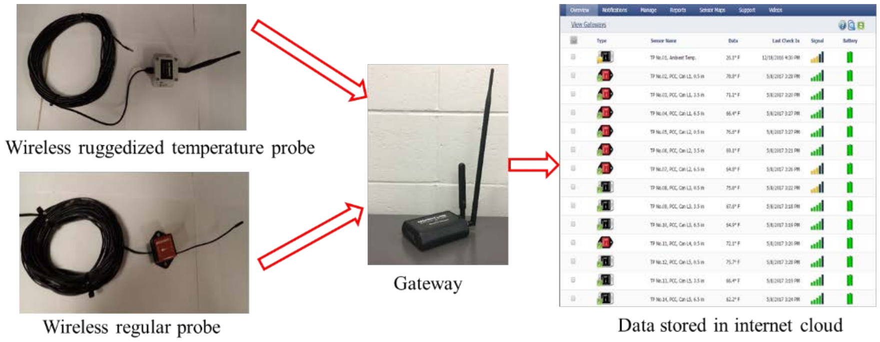


Figure 1. Monnit wireless sensor system.

The batteries for wireless probes are stored inside the wireless transmission units and can be easily replaced when power goes low. The ruggedized probe has a more water-resistant packaging with battery lifetime up to 8 years compared to the regular probe, which has battery lifetime up to 3 years (Monnit 2017). Additionally, the Monnit wireless temperature probe can have accuracy up to +/- 0.25 °C (0.45 °F) after calibrations. However, prior to field application at each airport, all the wireless probes were tested together and the results were compared with the commercial temperature sensors including thermocouples and Sensirion Relative Humidity (RH) sensors (SHT 71). The sensors exhibited almost same temperature readings with 0.3 °C maximum difference in the lab. In this study, the efforts required in instrumenting Monnit wireless sensor system in airports are elaborated.

CASE STUDIES FOR IMPLEMENTING WIRELESS SENSING SYSTEM FOR AIRFIELD PAVEMENT CONDITION MONITORING

Des Moines International Airport (DSM). In fall 2016, two Electrically Conductive Concrete (ECON)-based test slabs for heated pavement system (HPS) applications were constructed in the north General Aviation (GA) apron nearby Building 69 at the DSM airport. The slabs were structurally symmetrical and their dimensions were 4.6 m (15 ft.) long by 3.8 m (12.5 ft.) wide. Each slab consisted of a 9 cm (3.5 in.) ECON top layer and a 10 cm (4 in.) Portland cement concrete (PCC) bottom layer. Six heating electrodes were installed in each slab to prevent ice and snow accumulation on pavement surface. The wireless sensors, including ruggedized temperature probes, RH probes, current meters, and voltage sensors, were instrumented to monitor pavement conditions as well as to study heating efficiency of ECON HPS. A cellular gateway was placed inside garage for data uploading. In addition to the wireless sensors, a wired sensor system including Arduino based temperature sensors, strain gages, Sensirion RH sensors, and Decagon electrical conductivity (EC) sensors, were also installed. Figure 2 illustrates the sensor instrumentation plan for a typical test slab (see more details in Ceylan 2017).

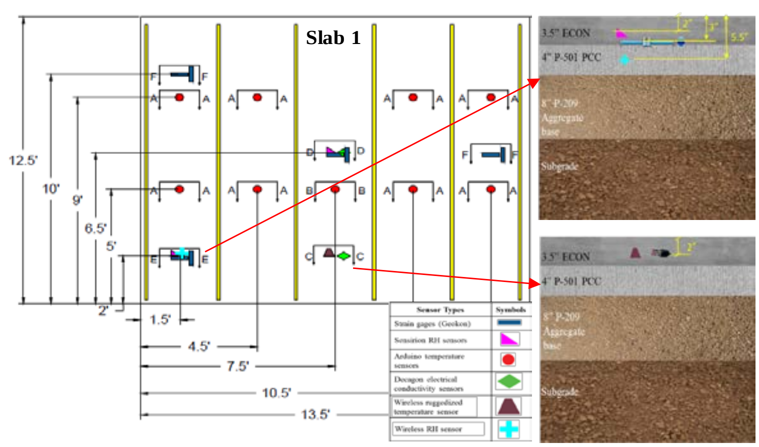


Figure 2. Sensor instrumentation plan in DSM.

According to Figure 2, it can be seen that two wireless RH probes were instrumented at the middle depth of the bottom PCC layer (see Figure 3(a)) and two wireless temperature probes were instrumented at the middle depth of top ECON layer (see Figure 3 (b)). The sensor heads were initially stored in a plastic box next to the test slabs and then transferred to a concrete box buried underground. The wired sensor were mainly instrumented in the ECON layer. All the cables were pulled through PVC conduits connected to data acquisition systems and power supply in the garage. A laptop was also used to upload the data from wired sensors to Internet.

(a) **(b)**

Figure 3. Sensor instrumentation for (a) bottom PCC layer, (b) top ECON layer.

Figure 4 illustrates the temperature data observed from the wireless probes. It can be seen that the ECON, with no application of electrical heating, had a peak temperature of almost 39 °C (102 °F) due to cement hydration, after which its temperature fluctuated in a range from 3 °C (38 °F) to 25 °C (77 °F) due to diurnal ambient temperature changes. The wireless temperature probes stopped functioning at the end of November 2016 due to water submergence of the wireless transmission units in the concrete box (see Figure 5). Wireless RH sensors in the bottom PCC layer had malfunctioned a few days after instrumentation, possibly due to the impact of a high alkali environment and high moisture content. The other wired sensors such as Sensirion RH sensors and Decagon EC sensors directly stopped functioning when the system were first turned on in early of December 2017 for heating test and then never recovered. Strain gages had minor effect when the electricity was applied. After one year’s monitoring period, only one strain gage malfunctioned in the early of 2017.

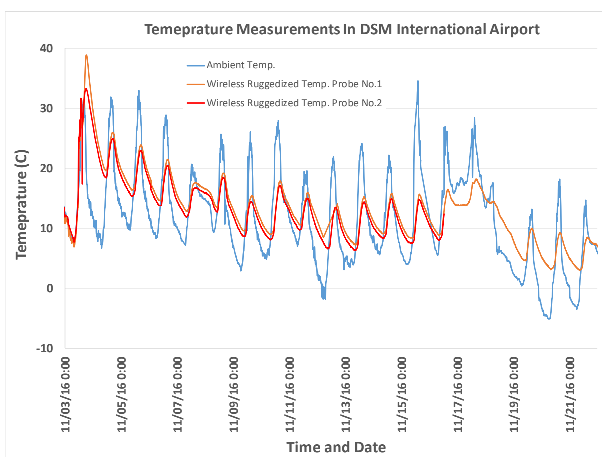
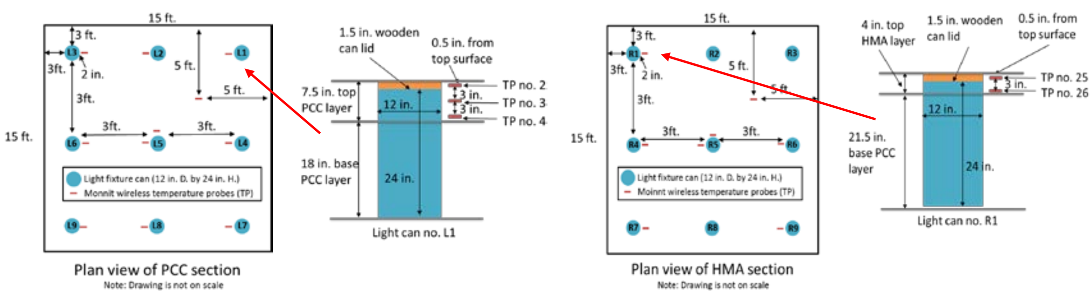


Figure 4. Temperature data from 11/03/2016 to 11/22/2016 in DSM.

Figure 5. Wireless transmission units submerged in water.

Ohio State University (OSU) Airport. In winter 2016, two pavement test slabs, a PCC slab and a hot mix asphalt (HMA) slab, were constructed on the north ramp of the OSU airport to capture cold winter weather effects on light-emitting diode (LED) operations. The PCC slab consisted of a 19 cm (7.5 in.) top PCC layer over a 46 cm (18 in.) PCC base layer, while the HMA slab consisted of a 10 cm (4 in.) top HMA layer over a 55 cm (21.5 in.) base PCC layer. Both test slabs had dimensions of 4.6 m (15 ft.) by 4.6 m (15 ft.). A 3 by 3 array of in-pavement runway lighting cans were also installed, which were covered by wooden lids during the paving stage. Wireless temperature probes were instrumented nearby light cans at desired depths (see Figure 6) to capture the effect from lighting operation on pavement temperature gradients.



(a) **(b)**

Figure 6. Layout plan of wireless sensors and LED light cans in the OSU Airport test site for (a) PCC slab, (b) HMA slab.

Figure 7 illustrates the sensor instrumentation procedures at the OSU test site. At this site, a total of 40 wireless probes including 26 ruggedized probes and 14 regular probes were installed for the two slabs. In PCC test slab, sensor instrumentation started on November 30, 2016. Prior to top PCC layer paving, sensor trees were made and then inserted into the holes drilled on the surface of base PCC layer (see Figure 7 (a)). All the wireless transmission units were stored in plastic boxes next to the PCC slab, with sink racks placed inside to protect them from water submergence. The boxes were completely sealed by heavy-duty bags and the exposed cables were covered by foam tubes (see Figure 7 (b)). During concrete pouring, plastic concrete from the drum mixer truck was also placed around the sensor trees in advance to increase sensor survival rate by mitigating the forces during concrete paving (see Figure 7 (c)). In the HMA slab, the wireless probes were instrumented about 6 hours after HMA layer construction on December 1, 2016. When slab cooled down, temperature probes were inserted at the desired depth in holes drilled through HMA layer, which were then sealed using asphalt sealant (see Figure 7(d)). The exposed cables were enclosed in flexible tubes to protect them from chewing by small animals. All the wireless transmission units were also sealed in boxes (see Figure 7 (e)). The wireless data acquisition system, including a 4G hot spot jetpack, a Wi-Fi bridge, and an Ethernet based gateway, were placed inside the garage about 3 m away from the test slabs (see Figure 7 (f)). After instrumentation, all the in-pavement probes were tested to function properly for data recording.

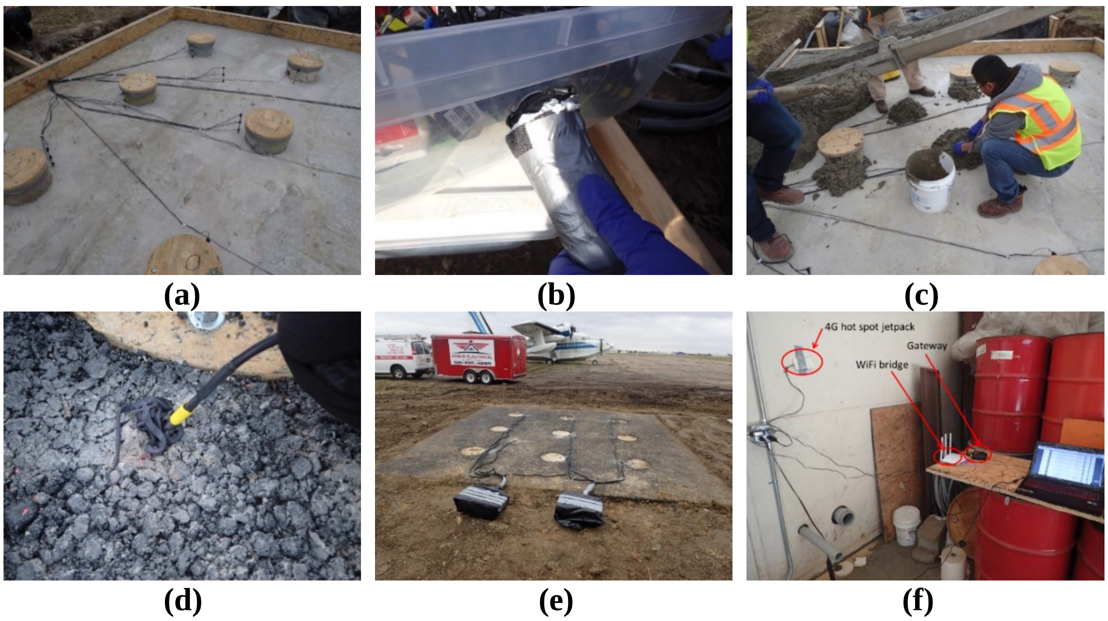
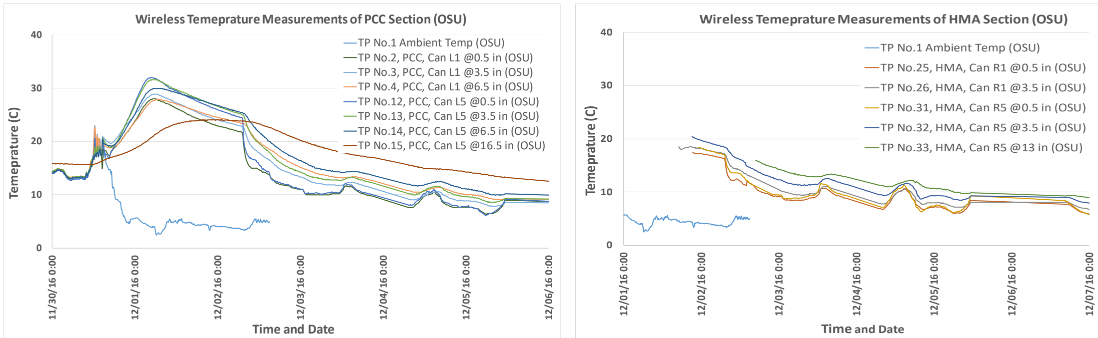


Figure 7. Sensor instrumentation in the OSU test site: (a) sensor trees, (b) cover exposed cables, (c) protect sensor trees during concrete pouring, (d) insert probes in HMA slab, (e) seal sensors in boxes, and (f) gateway.

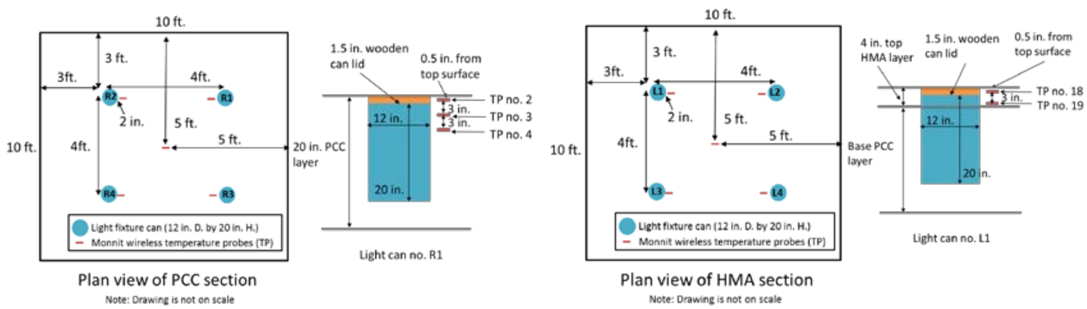
Figure 8 illustrates temperature readings obtained from OSU test site. After passage of time, temperatures of both slabs exhibited similar trends. Additionally, as the installation depth of probes increased, the nighttime temperature readings increased and the daytime temperature readings decreased. Surface temperatures were more prone to larger diurnal temperature fluctuations while those at the bottom usually exhibited smaller diurnal fluctuations. However, it can be seen that there were also some periods during which temperature probes were not able to upload data to the gateway, which could be variously caused by a temporally disabled 4G network, antenna issues. Additionally, after one year’s monitoring period, all the ruggedized probes are working properly while 7 out 14 regular probes have stopped functioning since early of 2017. The primary reasons can be attributed to battery issues. Most of the malfunctioned functioned probes were found to stop working when the temperature was below 4 °C (40 °F). The battery power of these probes was also lower than 60% while other functional probes had almost 100% battery power.



(a) **(b)**

Figure 8. Temperature data from 11/30/2016 to 12/07/2016 in OSU test site for (a) PCC slab, (b) HMA slab.

Texas A&M University (TAMU) Airport. Similar to the OSU airport test site, one PCC slab and one HMA slab were constructed at the TAMU Airport test site to capture effects of hot summer weather on lighting operations. In contrast to the OSU site, the two TAMU test slabs measured 3 m (10 ft.) by 3 m (10 ft.) with a 2 by 2 array of lighting cans 51 cm (20 in.) in height. The PCC slab consisted of a 51 cm (20 in.) thick PCC layer while the HMA slab consisted of a 10 cm (4 in.) top HMA layer over a 41 cm (16 in.) base PCC layer. Temperature probes were installed around light cans at various depths (see Figure 9). The sensors were instrumented on May 2017 using the same procedures as those adopted at the OSU test site (see Figure 10).



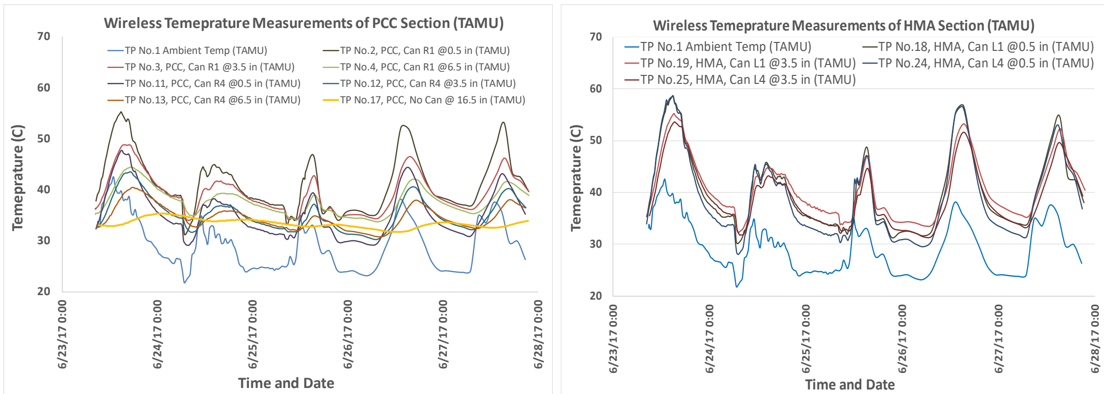
(a) **(b)**

Figure 9. Layout plan of wireless sensors and LED light cans in the TAMU test site for (a) PCC slab, (b) HMA slab.

(a) **(b)**

Figure 10. Sensor instrumentation in the TAMU site (a) PCC slab, (b) HMA slab.

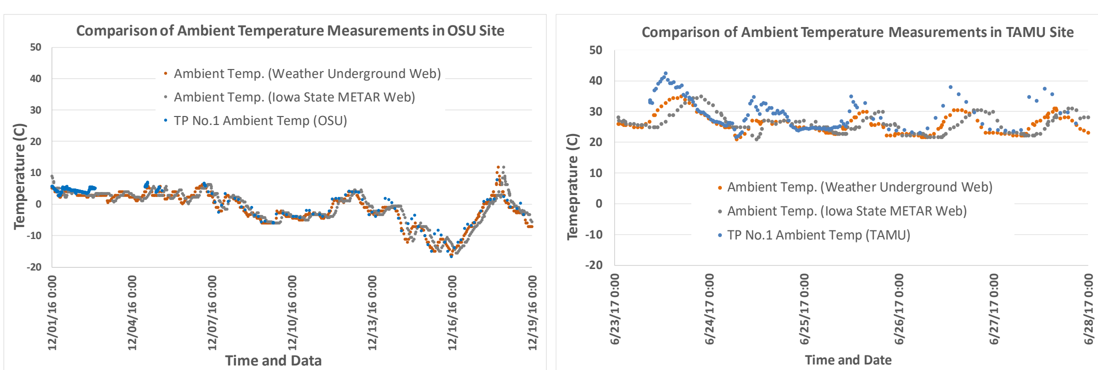
At the TAMU site, a total of 28 wireless probes including 11 ruggedized probes and 17 regular probes were installed. Figure 11 illustrates the temperature profiles obtained from this test site. The surface temperatures exhibited larger diurnal fluctuations compared to the bottom temperatures. As expected, the HMA slab at the TAMU site exhibited a higher temperature than the PCC slab under solar radiation. After half year's monitoring period, only one regular probe stopped functioning due to battery issues diagnosed by the system.



(a) **(b)**

Figure 11. Temperature data from 6/23/2017 to 6/28/2017 in TAMU Airport test site for (a) PCC slab, (b) HMA slab.

Figure 12 illustrates ambient temperature comparisons using the wireless temperature probes and other sources such as Weather Underground (WU 2017) and Iowa State METAR (Iowa Environmental Mesonet 2017) websites at the OSU and TAMU test site. The temperatures measured from the ambient temperature probes and the weather forecast websites generally show similar trends at both sites. However, the temperature probe yields higher temperature readings during daytime at TAMU site while the nighttime readings were almost the same as those from the websites. The main reason for the higher readings from the wireless temperature probe could be the strong solar radiation on the tip of probe, which was made of stainless steel. Additionally, temperature from temperature probes and WU website were slightly delayed compared with the Iowa State METAR website's database.



(a) **(b)**

Figure 12. Ambient temperature comparison for (a) OUS site, (b) TAMU site.

LESSONS LEARNED FROM FIELD CASE STUDIES

At the airport test sites, a mix of wireless ruggedized and regular temperature probes and wireless RH probes were installed, with all the sensors survived after layer construction. However, as time went, the wireless sensors started malfunctioning or losing signals due to various reasons, including damage of sensing and wireless transmission unit damage, network failure, battery issues, signal interference, extreme environmental conditions, and surrounding barriers between the sensors and gateway. In this study, it is found that the protection of the wireless transmission units from water accumulation and submergence is one of the most critical factors in achieving successful use of long-term sustainable wireless sensor systems in the field. Storing wireless transmission units above ground and sealing those using waterproof packaging (i.e., vinyl heavy-duty bags) have been proved to be a reliable way to keep wireless transmission units safe from water. Furthermore, concrete can provide high corrosive environment so proper coating (i.e., epoxy coating) on the sensing unit can help extend the monitoring period of sensors.

The wireless sensor systems instrumented also experienced periodical 4G network failure, which resulted in lots of data gaps during the monitoring period. The 4G hot spot jetpack device can easily malfunction in the field due to hardware issues so proper device protection and data backup are necessary as well. Battery is another important factor for long-time condition monitoring. In the field, the battery life could diminish when the temperature are either too high or too low. Monitoring of battery status can help be aware of battery related problems and warn the users if battery power goes low. Signal interference is also crucial for wireless sensor systems. Most wireless sensors were Radio-frequency (RF) based so the interference may exist due to neighboring radio hardware, environmental conditions, and presence of obstacles. In the field application, it is found that the signal interference would be generated when the two antennas are too close to each other. A minimum of 5 cm (2 in.) clearance distance could be recommended for arrangement of wireless sensor array based on field experience. Based on observations, wireless ruggedized probes also have better and more stable signal strength than regular probes. They also show less influence from small antenna distance. Additionally, it is also found that communication range between wireless sensors and gateway can be diminished as well due to extremely cold weather and surrounding barriers. For reliable wireless sensor network setup, it is better that the horizontal distance between wireless sensors and gateway is less than 15 m in winter when barriers (i.e., metal wall of the garage) exist. The antenna of the sensors and gateway should keep straight up and parallel to each other for maximum signal strength for communication.

SUMMARY

This paper describes wireless sensor system utilized for pavement condition monitoring at the Des Moines International Airport (DSM), the Ohio State University (OSU) Airport, and the Texas A&M University (TAMU) Airport. A wireless sensor system consisting of both ruggedized and regular temperature probes and relative humidity (RH) sensors was introduced. The procedures for wireless sensor instrumentation in PCC and HMA pavements were elaborated, and airfield pavement temperature profiles under diurnal environmental loads were also presented. Based on field experience, that key factors for achieving long-term sustainable wireless sensor systems are protection of wireless transmission units from water, reliable network setup, battery-power monitoring, and effective arrangement of sensor array. The wireless systems introduced at all the sites were able to send a warning message once the battery power was lower than 15%. While wireless sensor systems provide more flexible design and cost-effective sensor instrumentation for airfield pavement condition monitoring, current strategies of using wireless sensors in airfield are still limited to apron areas. Implementation of wireless sensor systems for taxiways or runways is still challenged due to requirements for equipment storage and protection of wireless transmission units, as well as potential Radio Frequency (RF) interference between in-pavement wireless sensors and loads from airplane take-offs or landings.

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